Plasma Wave Assisted Recombination

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In a collisionless, magnetized plasma, electron-proton recombination can be facilitated by a coupling of the particles to Landau damped plasma waves. The mechanism is similar to radiative recombination except that here the plasma wave, rather than an electromagnetic wave, carries energy away from the particle pair. In the presence of a magnetic field, electrons and protons form guiding center pairs which $\mathbf{E}\times\mathbf{B}$ drift in each other's field. The resulting oscillation is usually slower than a plasma oscillation; thus the particles can couple effectively to magnetized plasma waves. As the particles lose energy to the plasma wave, they move closer together.

In this analysis, the weakly bound guiding center atom is approximated as a finite size dipole oscillating at a time invariant frequency. A finite temperature kinetic approach identifies a Landau damped plasma wave driven by the dipole oscillation. The rate at which dipole energy radiates through the plasma wave is then calculated based on the dipole's interaction with this wave. The energy loss rate is calculated numerically for a range of dipole oscillation frequencies. Approximate analytic expressions for the rate are also derived to find the scaling of the damping. The Fourier space distribution of energy radiated from the dipole through the plasma wave is found to differ considerably from that predicted by cold fluid theory.

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The trapping and accumulation of slow positrons for use in studies of Rydberg states of positronium

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Though positronium has been well studied since its discovery over fifty years ago, little work has been undertaken on the Rydberg states of the system in high magnetic fields. Studies to probe these states are planned at Swansea, using laser spectroscopy and other methods. To provide the necessary number of positrons on demand for the generation of Ps, a compact accumulator using a buffer gas system has been constructed and tested, results of which will be reported. Simulations on the 10 Hz pulsing stage of the accumulator have been performed using SIMION v7.0, and have found that nanosecond timing resolution of the output positron bunch is attainable at distances from the trap of ~0.5 m, where a target would likely be located for Ps formation. This matches very well with the ~10ns time width of the 10 Hz laser pulse (spanning the spectrum from UV to IR), and the ~140 ns lifetime of the Ps ground state. A general overview of the Ps experiment will be presented, and intriguing observations of fluctuations in positron moderation efficiency using a solid neon film will be featured.

A Multicell Trap To Confine Large Numbers of Positrons[+]

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There are a number of motivations to develop the capability to accumulate large numbers of positrons and create high-density positron plasmas. Applications include positron storage for antihydrogen production, electron-positron plasma studies, Bose-condensed positronium, and the development of portable antimatter traps. Here we discuss a novel, multi-cell Penning-Malmberg trap designed to confine $N > 10^{12}$ positrons in plasmas with lifetimes of days or longer [1].

The design calls for a magnetic field ~ 10 tesla to confine the plasma in a cryogenically cooled electrode structure (T ~ 10 K). One set of constraints on the operating parameters arises from the outward, asymmetry-driven transport and the associated expansion heating. For design purposes, empirical transport scaling was used, based on experiments with electron plasmas. While the net outward transport can, on average, be cancelled by radial compression using a rotating electric field, there will still be expansion heating that must be balanced by cyclotron cooling. Another key constraint is the maximum electrical potential that can be applied to the confining electrodes (V ~ 10 kV assumed). The transport and cooling considerations favor high plasma temperatures which, for positrons, will be limited by positronium atom formation on background gas ($p \sim 10^{-12}$ torr).

These considerations lead to a multicell design in which separate plasmas are confined in cylindrical electrodes ~ 1 cm in diameter and 1 cm in extent along the magnetic field. Typical plasma parameters are T ~ 2 eV, $n \sim 10^{11}$ cm^{-3} and a plasma radius ~ 1.5 mm. A trap for 10^{13} positrons would consist of 10^3 cells, housed in an electrode structure 15 cm in diameter and 30 cm long and immersed in a common 10 T field. The considerations that lead to these operating parameters, other facets of the design, and variations on this general scheme will be discussed. Besides verifying that these design parameters can be achieved, challenges in building such a trap include developing techniques to fill the cells (i.e., both those across the magnetic field and in-line along the field) with a minimum of active control.

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Transfer, stacking and compression of positron plasmas for antihydrogen formation

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The antihydrogen formation rate in a nested Penning trap depends crucially on the density and temperature of the positron plasma. A similar observation pertains to the cooling rate of eV antiprotons released into a cold positron cloud. To date, buffer gas positron accumulation produces the largest number of trapped positrons per unit time. Therefore, the ATHENA collaboration decided to use a modular experimental system. This included interfacing a positron accumulator to an open antiproton capture and cooling trap. Whereas the positrons are accumulated in a 14 mT solenoid the antihydrogen formation takes place in the same 3T superconducting solenoid as used for the antiproton trapping. A "ballistic" method is presented for transferring positron plasmas from the accumulator into the combination area. The results of transfer and retrapping experiments will be reported together with the results from our stacking and compression experiments.

Long-Term Confinement of Dense Positron Plasma*

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Efforts to increase the storage levels of positrons in Penning-Malmberg and other types of traps are important for many applications. Energy from 0.511 MeV gamma rays generated through electron-positron annihilation can be used to heat working fluid such as air in a positron-powered turboramjet. Positronics Research LLC (PRLLC) is developing a storage trap that will host several positron, electron, and mixed plasma experiments intended to maximize storage conditions for positrons with acceptable lifetimes. This challenge requires development on two levels: computation and experiment. A 7”, warm-bore 5 T cryomagnet with three independently controlled solenoids is being procured. The central solenoid is 125 cm in length, and will be used for Penning-Malmberg trap studies. The end coils with lengths of each 15.25 cm will be used for magnetic mirror and other pinch-storage research experiments. These end coils can also extend the length of the magnetic field to facilitate injection and extraction. The end potentials of the Penning-Malmberg trap will be raised to 100 kV, creating an effective well of length 100 cm and diameter of 7.75 cm. One of the end-potentials is pulsed to lower its potential by ~1.5 kV during electron injection. Optimization of the radio-frequency drive system, designed to control the plasma using Trivelpiece-Gould modes, and assessment of diocotron instabilities of the non-neutral plasma are being investigated using a 16-node, distributed Linux cluster. The cluster is initially running an electrostatic particle-in-cell code to study three-dimensional plasma phenomena. Currently underway are the assembly phase and computational verification efforts. Experiments should begin in approximately six months.

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Can Shear Modes Be Excited and Detected in Penning Trap Ion Crystals? *

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We will describe our experimental efforts to excite and detect shear modes with laser-cooled, crystalline Be^+ ion plasmas in a 4.5 T Penning trap. Shear modes exist only in a crystalline (as opposed to a liquid) plasma and provide a sensitive probe of the ion correlations. They are also the lowest frequency modes of the system, and therefore could be an important factor in determining the usefulness of the Penning trap for quantum information experiments. The lowest frequency shear mode is an approximately rigid azimuthal oscillation of the crystal in the frame of the rotating wall. The detection and study of this mode would characterize, for the first time, the restoring force of the rotating wall in the crystalline regime, where phase-locked control of the plasma rotation is possible [1].

We trap and laser cool plasmas consisting of ~1000 to ~30 000 Be^+ ions to mK temperatures where they form crystals [2,3]. We work at low rotation frequencies $\omega_r << \Omega_c/2$ (Ω_c = cyclotron frequency) where the ion motion perpendicular to the magnetic field is governed by ExB dynamics. In this limit shear modes consist of azimuthal as well as radial oscillations. We attempt to excite these modes by phase modulation of the rotating wall. Shear modes are difficult for us to detect because of their low frequency (< 1 kHz) and because they appear to be damped at small excitations. Current attempts to detect the modes use real images of the ions to look for an azimuthal ion motion. We also plan to look for radial ion motion. We will discuss the different possibilities for detecting these modes and summarize our attempts to implement them in the lab.

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Ultracold Plasma Imaging

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We create ultracold neutral plasmas by ionizing laser-cooled strontium near the ionization threshold. The energetics of the plasma is determined entirely by the photoionization process, and we find the initial electron energies range from 1-1000K. The ion densities in the plasma can be as high as 10^{10} cm^{-3}, and are currently studied using charged particle detection schemes. However, since strontium ions have optical transitions in the visible, we can optically image the density profile via the Sr^+ $\mathbf{^2S_{1/2}} \rightarrow \mathbf{^2P_{1/2}}$ transition using 422nm light. We are currently constructing a laser system that will produce this light by frequency doubling a high-power at 844nm diode laser in a linear enhancement cavity for the infrared.

422 nm photons will be scattered or absorbed by strontium ions and imaged with an intensified CCD camera. From this method, we expect to resolve the density profile of the plasma, and observe kinetics on a sub-microsecond time-scale. Results from plasma studies and progress towards imaging will be presented.

Attractive Potential via Thermionic Emission

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The study of charging of objects immersed in a plasma is a classic problem of plasma physics with many applications [1], ranging from space problems to dusty plasmas to probe theory for plasma diagnostics. Often the description of the charging of an object immersed in a plasma can be reduced to the progressive charging of the object by the plasma particles that randomly hit its surface and are captured. In absence of other processes, the higher mobility of the electrons leads to negatively charged objects.

However, often, other processes need to be considered. For example, if the object immersed in the plasma is sufficiently heated, a significant number of electrons can be emitted by the thermionic effect, altering the balance between electron and ion captures; this can reduce the negative charge on the object, or even reverse its polarity. An example is given by small objects entering the Earth's atmosphere (meteoroids). In fact, recent work has shown that the heating of the meteoroids due to the interaction with the atmosphere can produce a considerable thermionic effect which leads to positively charged meteoroids [2].

The present work deals with the charging mechanism of a small, spherical meteoroid, immersed in a plasma, in presence of thermionic emission. The investigation has been carried out by using a spherical Particle-In-Cell (PIC) method. The peculiarities of the problem under consideration require special boundary conditions: at the outer boundary we inject plasma particles in order to represent an infinite plasma medium outside the simulation domain. This approach effectively represents an infinite plasma and can describe correctly the dynamics of the system. The results of our investigation are listed below.

First, we show numerical simulations of small (with respect to the linearized Debye length) meteroids. As expected, our results are in agreement with the orbit motion limited (OML) theory: depending on the work function of the meteoroid, the object can be charged negatively or positively and the shielding potential is well described by the monotonic Debye-Huckel potential with screening length given by the linearized Debye length.

Second, we focus on large meteoroids. In this cases, the OML theory is expected to fail [3-5]. Our results show that the OML theory becomes unreliable even if one considers the electron Debye length as the screening length. Furthermore, rather unexpectedly, the potential around the object is not monotonic (as predicted by the OML theory) but a potential well appears. The consequences of this effect can be considerable since potential wells can provide regions of attraction for other objects with the same sign of charge.

Third, we speculate that this effect could be tested experimentally. We propose that UV light added to current experiments can create the conditions for the formation of attractive potentials between dust particles. Such experiments would be best conducted in microgravity (e.g. on board the International Space Station Alpha) where other attractive mechanisms (e.g. wake field, ion flow alignment) are not present.

Fourth, we investigate the influence of the plasma and grain parameters (i.e. density, temperature, work function) on the shielding potential around the grain, considering both laboratory and space conditions.

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Use of a Magnetic Nozzle and Diverter Electrode to Enhance System Efficiency in a Penning Fusion Reactor

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Abstract

Inertial Electrostatic Confinement of fusion ions in a modified Penning trap is further modified to include a mechanism for low-power recirculation of electrons via a diverter electrode placed in the low-field, cusp region of the trap. The locally divergent magnetic field lines act as a magnetic nozzle to extract energy bound up in the angular momentum of the larmor gyrations of the electrons, enabling the diverter potential to be close to that of the emitter while still collecting scattered electrons. The diverter recirculates a large fraction of the scattered core electron population back to the emitter through a much smaller voltage drop than the anode-emitter potential difference, thereby reducing the overall power consumption for a given collisional diffusivity in the beam and improving overall system efficiency. Modeling of the system is presented in an attempt to roughly quantify the potential efficiency improvement. An experimental evaluation of this technology is proposed, and reference is made to the possibility of the development of this type of Penning Fusion Reactor as a neutron source.

Assessment of the Axial Plasma Loss Rate in a Malmberg-Penning Trap. Y. Chang and C. A. Ordonez, University of North Texas. -- Suppose that at times t < 0, the plasma in a Malmberg-Penning trap has a Maxwellian velocity distribution. If the depth of the one-dimensional electrostatic well that confines the plasma axially is suddenly reduced (made shallower) at time t = 0, the evolution of the velocity distribution can be described relative to a time period, □. The time period □ is defined as the time required for plasma particles in the tails of the distribution to be lost from the trap after no longer being confined by the well. Suppose that during times 0 < t < □, the effect of collisions on the evolution of the velocity distribution is negligible, and all the particles that exist in loss regions in velocity space leave the well. Then, at time t = □, the velocity distribution of the plasma is a cutoff Maxwellian. For times t > □, the plasma loss rate can be expected to decrease with time, and the plasma's velocity distribution is no longer describable as a cutoff Maxwellian. Most of the existing theories that can be used for predicting the plasma loss rate at times t ≥ □ are reviewed in Ref. [1]. The theories were developed to apply for plasma confinement in the presence of a one-dimensional well, were developed primarily for describing hot fusion plasmas in magnetic mirrors, and were developed in the limit that the plasma temperature (in energy units) is small compared to the depth of the one-dimensional potential energy well [1]. In the work to be presented, a theory is developed for predicting the collision-based axial loss rate of a plasma in a Malmberg-Penning trap for any ratio of the plasma temperature to the depth of the particle potential energy well. A cutoff Maxwellian velocity distribution is considered for the plasma, and the theory applies at a time, t = □, just after direct (non-collisional) axial losses become negligible following a sudden reduction in the depth of the axial electric potential well. Consequently, a loss rate prediction that is made with the theory is expected to provide an upper limit for the collision-based axial plasma loss rate after the axial well is suddenly made shallower. Various assumptions are made in developing the theory. The axial well is assumed to be a square well, the plasma properties are assumed to be uniform within the well, and the particle mean-free-path is assumed to be much larger than the plasma dimensions. A derivation for an integral equation that describes the axial plasma loss rate is provided, and a Monte Carlo computational approach is presented for numerically solving the integral equation. Example predictions are provided, and comparisons with existing theories are made. The theory presented is intended to be useful for predicting the transient confinement properties of a plasma species within the inner well of a nested Penning trap. Such a trap has been used to produce antihydrogen [2,3].

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Electrostatic Confinement of a Reflecting Ion Beam. J. R. Correa and C. A. Ordonez, University of North Texas. -- Charged particles that experience an electric potential that periodically changes can be considered to be acted on by an effective force, which can be used to confine the particles. The electric potential can change either periodically in time, as in a Paul trap, or periodically in the spatial region through which the charged particles travel, as in an ion-trap resonator [1]. An ion-trap resonator employs a static electric field and no magnetic field to confine charged particles within a long, cylindrical, axially symmetric confinement region [1]. An electric potential well provides axial particle confinement. Radial particle confinement occurs because the particles travel axially through a spatially periodic electric potential that provides an effective force that is directed radially inward. Two modes of operation have been reported for the ion-trap resonator. For each, an ion bunch is initially caught in the trap having an axial length that is smaller than the axial length of the confinement region. In one mode of operation, the ion bunch quickly spreads out axially during a time period that is short compared to the particle confinement time [1]. In the other mode of operation, referred to as synchronization, the length of the ion bunch remains smaller than the axial length of the confinement region [1]. For the first mode, the particle velocity distribution is describable as that associated with a reflecting ion beam after the ion bunch spreads out axially. Even with a non-Maxwellian velocity distribution, long particle confinement times appear possible. Experimentally measured confinement times in excess of 2 s where reported in Ref. [1] for the first mode, and a confinement analysis presented in Ref. [1] is consistent with the following hypothesis for explaining the long confinement time: The effect of periodic particle collisions among themselves, which tends to cause the velocity distribution of the trapped particles to become Maxwellian, is counteracted by the effect of periodic particle encounters with focusing-field regions, which tends to cause the velocity distribution of the trapped particles to remain non-Maxwellian. In the work to be presented, a classical trajectory Monte Carlo simulation is used to explore various configurations in which electrostatic confinement of a reflecting ion beam may be possible. Preliminary results indicate that a reflecting ion beam can be confined within a simple configuration consisting of three cylindrical electrodes that are aligned end to end. The work reported also includes an assessment of the possibility of using an ion-trap resonator for trapping two oppositely signed particle species. One possibility is to form a nested well configuration similar to one of those described in Ref. [2]. Another possibility is to combine traps such that two or more reflecting beams intersect each other. A virtual anode (cathode) may be expected to form where two or more positive (negative) beams intersect, and a three-dimensional well may form within which electrons (positrons) can be confined. Possible applications of electrostatically trapped, reflecting ion beams include antihydrogen and fusion energy production. For antihydrogen production, the possible detrimental effect that a magnetic field can have on the three-body recombination rate [3] can be made negligible. For fusion energy production, a large number of reflecting beams could be arranged to intersect a central location, and the inertial electrostatic confinement concept could be implemented in the "star" mode of operation [4] with the possibility of enhanced ion confinement.

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Interdisciplinary Issues Associated With Generating a Fully Non-Neutral Fusion Plasma. C. A. Ordonez, University of North Texas. -- A fully non-neutral plasma is considered for application as a fusion plasma. A fully non-neutral plasma is defined at present as a plasma consisting of charged particles having the same sign of charge, while a fusion plasma is defined as a plasma within which nuclear fusion reactions are taking place at a useful rate. An advantage of using a fully non-neutral plasma as a fusion plasma is that plasma energy loss mechanisms would not include processes dependent on the presence of electrons, such as electron thermal conductivity and electron cyclotron and bremsstrauhlung radiation. A disadvantage with using a fully non-neutral plasma as a fusion plasma is that the average fusion reactivity can be considerably limited. The average fusion reactivity is defined as the number of fusion reactions that occur per unit time per unit volume of the plasma confinement apparatus. In the work reported, interdisciplinary issues that can lead to a limited average fusion reactivity are identified. Interdisciplinary issues are defined as involving disciplines outside of plasma physics. For example, the possibility of electric breakdown at a solid surface due to the electric field produced by the plasma is considered an interdisciplinary issue. Disciplinary issues and questions associated with fabrication and assembly accuracy are not considered. An example of a disciplinary issue is whether the Brillouin density limit can be exceeded to obtain a magnetically confined fully non-neutral fusion plasma [1,2]. It should be noted that this work is intended to be somewhat pedagogical in simplicity, and only issues specific to fully non-neutral plasmas are identified. The issues identified should be considered for initiating any new study on the prospect of producing an electron-free fusion plasma. Although many of the issues identified are likely known to researchers who have already undertaken such studies, the present work is intended to serve as a systematic compilation of the interdisciplinary issues. Various forces that might be combined to obtain a plasma confinement equilibrium are considered. The forces are the electric, magnetic, magnetic gradient, periodic potential, and centrifugal forces. The "periodic potential" force refers to an effective force produced on charged particles that move through spatially periodic changes in electric potential. The operation of an ion-trap resonator provides an example of the use of such a force [3]. The electric and magnetic fields that would be used to produce the first four of the forces are assumed to be time independent for the analysis. The magnetic gradient and periodic potential forces arise from the magnetic force and electric force, respectively. However, for convenience, the magnetic gradient and periodic potential forces are considered as a separate forces. Five plasma confinement geometries are considered, spherical, cylindrical, planar, toroidal, and hollow-cylindrical. The toroidal configuration is only considered in the cylindrical limit, while the hollow-cylindrical configuration is only considered in the planar limit.

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Highly charged ion confinement in electron beam ion traps

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In an electron beam ion trap (EBIT) highly charged ions are confined by the combination of electrostatic and magnetic fields and the space-charge potential of an intense electron beam in the center of the device. The electron beam serves several purposes, from creating highly charged ions via successive ionization processes, through contributing to the radial and axial confinement of the ions. The ion cloud itself is a dynamic multi-component entity, in which ionization, recombination, cooling, and heating processes are in a fine balance with each other.

At first sight the high-energy and high current electron beam might seem to be a strong disturbance in the trapping properties of EBITs compared to other Penning type of devices. However, the combination of the strong electrostatic attraction of the electron beam with the high charge of the ions can create situations where certain plasma properties of the ion cloud can fall into interesting parameter regions. In EBITs for example it is natural that ion densities exceed the Brillouin density limit that is calculated for a plasma radially confined purely by magnetic fields.

In order to understand the confinement properties of the EBIT plasma and to investigate the feasibility of reaching critical parameter regions our group has set out an experimental program to study the highly charged ion cloud of the device. Since the electron beam ion trap is well suited for diagnostics via the detection of electromagnetic radiation emitted by the ions, imaging and spectroscopic methods can be extensively used in these studies.

In this presentation we will survey our recent results. X-ray and visible spectroscopy combined with the systematic change of the electron beam current and the trapping voltages allowed us to study a variety of effects.

Trapping of Rare Isotopes at the NSCL at MSU

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The Low-Energy Beam and Ion Trap Project LEBIT opens the door to a new class of experiments at the NSCL at MSU. The Coupled Cyclotron Facility delivers a large range of rare isotopes with high intensities. LEBIT converts these beams into low-energy beams with excellent quality by using gas stopping and advanced ion guiding, cooling, and bunching techniques. These rare isotope beams can then be used for precision experiments like Penning trap mass spectrometry or laser spectroscopy. In recent years quite a number of precision trap and trap-type experiments have been coupled to rare isotope facilities, many more are about to become operational. In order to study the most exotic and interesting yet rarest and most short-lived species available it is mandatory to improve existing beam handling and trapping techniques as well as to employ new concepts.
LEBIT uses two ion traps for this purpose, one for beam cooling and bunching and one for precision mass measurements and decay studies. The LEBIT ion cooler and buncher is an advanced system based on a linear radiofrequency ion trap. Compared to similar ion bunchers already in operation it has several new features like the usage of wedge-type electrodes for providing the drag force along the axis of system or its operation at cryogenic temperatures. The LEBIT Penning trap system uses a superconducting magnet with a field strength of 9.4 T and an improved time-of-flight detection scheme for the cyclotron resonance detection. Numerical simulations have been carried out on octupole excitation of the ion motion in the LEBIT trap, which in principle may be a way to further improve the mass resolving power in Penning trap mass spectrometry.

Review of the High Performance Antiproton Trap (HiPAT) experiment at the Marshall Space Flight Center

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The significant energy density of matter-antimatter annihilation is attractive to the designers of future space propulsion systems, with the potential to offer a highly compact source of power. Many propulsion concepts exist that could take advantage of matter-antimatter reactions, and current antiproton production rates are sufficient to support basic proof-of-principle evaluation of technology associated with antimatter-derived propulsion. One enabling technology for such experiments is portable storage of low energy antiprotons, allowing antiprotons to be trapped, stored, and transported for use at an experimental facility.

To address this need, the Marshall Space Flight Center's Propulsion Research Center is developing a storage system referred to as the High Performance Antiproton Trap (HiPAT) with a design goal of containing 10^{12} particles for up to 18 days. The HiPAT makes use of an electromagnetic system (Penning-Malmberg design) consisting of a 4 Telsa superconductor, high voltage electrode structure, radio frequency (RF) network, and ultra high vacuum system. To evaluate the system "normal matter" sources (both electron guns and ion sources) are used to generate charged particles. The electron beams ionize gas within the trapping region producing ions *in situ*, whereas the ion sources produce the particles external to the trapping region and required dynamic capture. A wide range of experiments has been performed examining factors such as ion storage lifetimes, charge exchange with background gases, effect of RF energy on storage lifetime, and ability to routinely perform dynamic ion capture. In addition, plasma modeling efforts have been started using the XOOPIC code.

RF manipulation and detection of protons in the High Performance Antiproton Trap (HiPAT) experiment

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The significant energy density of matter-antimatter annihilation is attractive to the designers of future space propulsion systems, with the potential to offer a highly compact source of power. Many propulsion concepts exist that could take advantage of matter-antimatter reactions, and current antiproton production rates are sufficient to support basic proof-of-principle evaluation of technology associated with antimatter-derived propulsion. One enabling technology for such experiments is portable storage of low energy antiprotons, allowing antiprotons to be trapped, stored, and transported for use at an experimental facility.

The Marshall Space Flight Center's Propulsion Research Center has built a Penning-Malmberg trap referred to as the High Performance Antiproton Trap (HiPAT) with a design goal of containing 10^{12} particles for up to 18 days. Current efforts have been focused on improving the RF rotating wall system to permit longer storage times and non-destructive diagnostics of stored ions. Typical particle detection is currently performed by extracting trapped ions from HiPAT and destructively colliding them with a micro-channel plate detector (providing number and energy information). The improved RF system has been used to detect various plasma modes for both electron and ion plasmas in the two traps at MSFC, including axial, cyclotron, and diocotron modes. New diagnostics are also being added to HiPAT to measure the axial density distribution of the trapped cloud to match measured RF plasma modes to plasma conditions.

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Non-Neutral Plasma Physics at the University of Delaware[1] T. B. MITCHELL, B. T. CHANG, Z. SHANG, Department of Physics & Astronomy, U. Delaware, Newark, DE 19716 — Three new experiments are in the process of being developed, and we will present design details and describe their progress. An electron Malmberg-Penning trap with a phosphor screen imaging diagnostic and 6-fold azimuthally segmented electrodes is being constructed, principally to investigate the dynamics of gravitational[2] and geophysical fluids. An ion Penning trap with access for laser cooling and optical diagnostics is being constructed to investigate the dynamics of strongly-correlated plasmas, with a focus on the physics of the melting transition and the response of the one-component plasma to radiation pressure.[3] An RF trap is also being built to study high field laser-matter interactions in conjunction with the ultrafast laser group of Barry Walker. A design for an inexpensive radio-frequency oscillator for trapping particles which improves on the signal purity and turn-off time of an existing one[4] will be presented.

[1]Supported by the National Science Foundation and the U. Delaware Research Foundation.
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Experimental and Theoretical Studies of Electrostatic Confinement on the INS-e Device

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Recent theoretical works[1,2] have suggested that a tiny oscillating ion cloud immersed in a uniform electron background may undergo a self-similar collapse that can result in the periodic and simultaneous attainment of ultra-high densities and temperatures. The oscillating ion cloud (referred to as the Periodically Oscillating Plasma Sphere or POPS) is expected to be in local thermodynamic equilibrium at all times due to orthogonal relation between Gaussian distribution in space and Maxwellian distribution in velocity of the harmonic oscillator. The POPS is stable to multidimensional perturbations, while its self-similar solutions appear to be attractors. Theoretical projections[1] have indicated that such a system may have net fusion gain even for an advanced fuel such as D-D. In addition, these systems have very favorable reactor attributes in that the total power scales inversely with the size, leading naturally to a modular, high mass power density device.

However, there are several issues that need to be resolved in order to determine the efficacy of this scheme. In particular, POPS requires a quiet virtual cathode with a harmonic potential well, which calls for control of the plasma density profile and its stability. This problem has been studied with our present program and appears to be tractable. A steady-state potential well containing a large number of background electrons has been created in our gridded electrostatic device without any apparent sign of instability. It has also been shown that the radial electron density profile can be varied to produce a desired near-uniform density by adjusting the bias voltages of the grids.

Based on this result, we are proposing to perform a number of critical experiments to test the feasibility of POPS. The stable virtual cathode formation will be tested in a parameter region relevant to thermonuclear reactions using a pulsed high-voltage operation. We will also investigate the phase locking and control of the POPS oscillation. Space charge neutralization of the ion collapse phase of the oscillation will be studied to test an achievable compression ratio. Additionally, we will extend our theoretical capability to include both ion and electron dynamics in order to understand the operation of POPS and to make direct comparison with the experiments.

Reduction of asymmetry transport in the annular Penning trap

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Transport by cross-field diffusion has been studied in the annular Penning trap in which a nonneutral plasma of electrons is contained between concentric cylinders.[*] At densities sufficiently low ($<10^5$ cm^{-3}) to suppress mobility transport arising from the space charge electric field, the dominant sources of transport are diffusion from collisions of electrons with added helium gas and asymmetry transport from stray fields. The collisional diffusivity scales linearly with collision frequency and inversely with the square of the axial magnetic field. The measured mean energy is initially 0.3 eV and the least energetic electrons are lost more slowly as a consequence of the energy dependence of the diffusivity. Decay constants are about a factor of four higher than calculated from the electron-helium momentum transfer collision frequency. Both the asymmetry transport and the collisional transport depend upon the cleanliness of the trap surfaces.

A coating of colloidal graphite on the plasma-facing trap surfaces increases the density decay time approximately an order of magnitude through reduction of the asymmetry transport. The longer confinement times are not useful for experiments, however, because the shot-to-shot reproducibility is spoiled by losses resulting from instability.

* Qudsia Quraishi, Scott Robertson and Bob Walch, Physics of Plasmas **9**, 3264 (2002).

Global Eigenmode Analysis of the Magnetorotational Instability in a Magnetized Dissipative Couette Flow

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The magnetorotational instability (MRI) is the most promising process to explain the outward angular momentum transfer in magnetized accretion disks. However, the laboratory testing of MRI is absent. Recently, two experiments have been proposed to observe MRI in a Couette flow of liquid metals in a rotating annulus [Ji, Goodman & Kageyama, MNRAS, 325, L1 (2001); Noguchi et al., ApJ, 575, 1151 (2002)].

Here we explore the possibility of observing MRI in a Couette flow of plasma. Local stability analysis shows the feasibility of observing magnetic field enhancement in both type of experiments. Resistivity and viscosity of plasmas can be varied quite widely unlike those of liquid metals. Both large and small Prandtl numbers are achievable with plasmas while liquid metals have very small Prandtl numbers. We show global axisymmetric and non-axisymmetric unstable eigenmodes and corresponding eigenfrequencies calculated by our newly developed code. The code solves the boundary value problem for the system of five linear second order differential equations in radial coordinate. Plasma MRI experiment is now building at P-24, LANL.

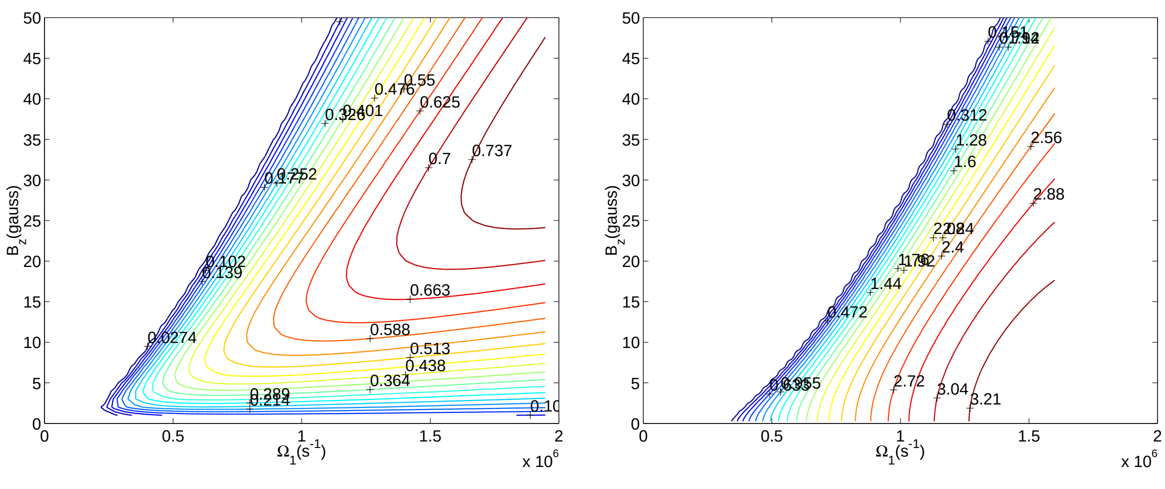

Fig. 1.— Growth Rate of the axisymmetric unstable MRI eigenmode.

Status of the design and construction of the Columbia Non-neutral Torus

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The Columbia Non-neutral Torus (CNT) is a tabletop (R=0.3 m, a=0.1 m, B=0.2 T) stellarator to be built at Columbia University. The goal of CNT is to study the equilibrium, stability, and transport of non-neutral plasmas confined on closed magnetic surfaces. CNT will use four circular coils, two interlocking coils with a variable tilt angle, plus
two additional poloidal field coils. By varying the angle between the interlocking coils, the rotational transform can be varied from 0.2 to 0.6 and the magnetic shear from essentially zero to 20%. The results of a numerical study of how error fields affect the quality of the magnetic surfaces will be presented. CNT is designed to reach neutral pressures of
$2*10^{-10}$ Torr. Details of the vacuum chamber and vacuum pump system will be presented. These are expected to be completed in July 2003. The electrons will be injected from a multi-sectioned tungsten filament probe placed directly on the magnetic surfaces. The bias voltage and current flowing through each section of the filament will be varied to explore a variety of emission profiles. The plasma will be diagnosed by numerous Langmuir and sector probes, connected to a PCI-based data acquisition and control system.

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Long Time Confinement of Toroidal Electron Plasmas in Proto-RT

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Toroidal traps have no open ends of magnetic field lines, and no electrostatic potential is required for the confinement of plasmas along the field direction. This feature might be advantageous for the containment of high-energy particles or simultaneous confinement of different charges at any degree of non-neutrality. Recently, a high β equilibrium state with strong flow due to the electric field and resultant drift motion of non-neutralized plasma has been predicted by a two-fluid model [1]. Traps of anti-matters such as positron plasmas are also intensively studied in the fields of plasma and atomic physics. Focusing on these applications as well as its fundamental physics, toroidal non-neutral plasmas have attracted a renewed interest these days.

In this study, we report the confinement properties of toroidal electron plasmas in an internal-conductor system. Besides conventional toroidal magnetic field coils, Proto-RT (Prototype-Ring Trap) [2] has two kinds of poloidal field coils (dipole and vertical field coils). The use of these coils allows us to study toroidal electron plasmas in a magnetic-surface configuration [2,3]. For the optimization of electrostatic potential profiles, Proto-RT also equips a pair of electrodes in the confinement region of the torus [4]. By applying external radial electric fields, the structure of toroidal electron plasmas was substantially modified to form a stable equilibrium. When the electrode was negatively biased to cancel the hollow region of potential profiles, electrostatic fluctuations in a range of diocotron frequency were drastically suppressed. After the stop of electron injection, the amplitude of fluctuations dropped rapidly and the trapped charges adjusted to enter a quiescent phase. The characteristics of confinement time were investigated by the wall probe measurements; each shot of the measurements was artificially terminated and the remaining charge on the wall probe was measured. Electron plasmas in a number density of $\sim 10^{12} m^{-3}$ were confined in a decay time constant of 0.1sec in a dipole magnetic field configuration. Typical magnetic field strength was of the order of 0.01T. In the present base pressure of 10^{-6} Torr, the observed confinement time is comparable to classical diffusion time due to the collisions of electrons with neutral atoms.

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Parameter dependence of inward diffusion on injected electrons in helical nonneutral plasmas

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Experimental study on generation of nonneutral plasmas has been performed on a three dimensional helical magnetic configuration. The purposes of this study are to investigate the condition of electron plasma generation and its spacial structure in a helical field, and to systematically clarify the mechanism of electron plasma transport and stability in a non-uniform magnetic field.

In these days, many studies on plasma flow have been performed. For example, there are some works related to generation of the strong electric field on the boundary layer of the torus configurations in order to improve particle confinement by a fast flow there. When we think making this electric field by violation of the neutral condition of plasma, we have to keep the nonnertral state where interior charge balance is broken. On linear configurations such as Marmberg traps, the possibility of this state has been clarified. However, it is not known on the torus configurations. Especially, in a helical field with three-dimensional structure and rotational transform, it is very unclear whether we can inject electrons from exterior of the magnetic surfaces. And even if it is possible, it is not known that localized electric field can exist even in limited region of plasma boundary.

To investigate the things above, we have performed experiments of helical electron plasmas on the CHS (Compact Helical System) device. Magnetic field strength is variable. Electrons are injected from the electron gun which is settled on the stochastic region, exterior to the last closed flux surface (LCFS). We investigate the dynamics of helical electron plasmas by varying the position of electron source, initial velocity, density as well as the pitch angle to the field line. Electron penetration into the magnetic surfaces inside the helical field has been observed by flux measurements. And although the inward diffusion is a collisionless procedure according to the time scale of the signals, it is not just a orbital motion of electrons but some collective phenomena may drive the diffusion. Furthermore, although the electrons are injected from outside the LCFS, the spacial structure and the time transition of the helical electron plasma built by the inward diffusion strongly depend on the injection condition such as beam current and direction. These facts mean that helical electron plasmas are effected by the interface region or the stochastic region, and we are progressing further studies in accordance with the mechanism of the penetration and confinement of the electron plasmas in a helical configuration.